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Environmental and financial life cycle assessment of ‘open-renovation-systems’: methodology and case study

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Abstract

The emphasis in this research is on affordable and innovative semi-prefabricated ‘open-renovation-systems’ for extending residential buildings. Based on an existing LCA (life cycle assessment) and LCC (life cycle costing) methodology, two methodological issues in evaluating renovation interventions are assessed: (1) the allocation of the environmental impact of the existing structures and materials to the life cycle before and after renovation and (2) the energy calculation method. An existing semi-prefabricated ‘open-renovation-system’ for a rooftop extension is assessed both on element and building level from an environmental and financial life cycle perspective.

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Keywords: Life Cycle Assessment (LCA); Life Cycle Costing (LCC); sustainable renovation; rooftop extension; semi-prefabricated elements; allocation; building lifespan; energy calculations

1. Introduction

Renovation in Europe is mainly focusing on reducing the operational energy of buildings and hence has often a narrow scope regarding sustainability. A screening of current practices in Flanders (Belgium) confirms that renovations are often limited to small interventions to improve the energy performance and shows that these interventions often miss a long term vision. In Flanders, we are mainly dealing with a privative housing ownership and most of the renovation interventions are ad hoc solutions for ad hoc renovation questions. As these interventions

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are so specific, they are often expensive and time consuming. Examples in other contexts show that a different approach is possible.

In the Netherlands, for example, prefabricated industrial building systems are more and more used. As prefabricated building systems are assembled off-site, the work on-site is limited to the mounting of the prefabricated elements, attaching these elements on the existing structure and some finishing works. These aspects reduce the renovation time of a building to a few days, which leads to less disturbance for the neighborhood and the inhabitants of the renovated houses. The ‘Bestaande Wijk van Morgen’ project in Kerkrade West [1] and the passive renovation project ‘De Kroeven’ in Roosendaal [2] are two examples of large scale renovations projects in the Netherlands that used prefabricated elements for the building envelop renovation. These projects confirm that prefabricated industrial building systems can result in faster and affordable renovations. Beside these projects, some innovative European demonstration projects have been set-up in the last decades. TES EnergyFacade [3], IEA ECBCS annex 50 [4] and E2ReBuild [5] are some examples of such projects. These projects show that a high quality renovation can be reached by the use of prefabricated elements while inhabitants can remain in their houses during the renovation works. The TES Energy façade project shows furthermore the many possibilities of prefabricated elements for renovation with volume expansion [6].

Beside the problem of the ad hoc renovation market in Flanders, there is a need for a more flexible building stock. A growing Flemish population accompanied by a decreasing household size results in a need for additional houses [7]. The needs of a household moreover change over time, e.g. due to family expansion or contraction or evolving comfort requirements. A flexible and adaptable housing stock could hence contribute in the overall aim to move towards a more sustainable built environment. Interventions as splitting, combining and extending existing buildings are possible solutions to deal with these changing needs and to avoid spatially underused buildings and will be more and more required in the future. In order to execute these interventions in a sustainable manner there is a need for affordable and adaptable building systems with a low environmental impact.

This paper focuses on the assessment of the life cycle financial and environmental impact of rooftop extensions. The goal of the paper is twofold: (1) some methodological issues in evaluating renovation interventions are discussed and analyzed and (2) an existing semi-prefabricated ‘open-renovation-system’ for a rooftop extension is assessed both on element and building level from an environmental and financial life cycle perspective.

Nomenclature

LCA	Life Cycle Assessment
LCC	Life Cycle Costing
EDD	Equivalent Degree Day

2. Methodology

The assessment of the life cycle environmental impact of the rooftop extension is based on the Belgian MMG LCA method developed by OVAM [8]. This method follows an integrated life cycle approach, as recommended by the European standards EN 15804 [9] and EN 15978 [10] for the evaluation of construction materials and buildings. The MMG method considers the entire life cycle of the building, mainly classified as the initial stage, use stage and end-of-life (EOL) stage. The set of impact categories in this method not only includes the ones of the CEN standards, but comprises also seven additional impact categories (referred to as CEN+ indicators). The results are expressed in environmental costs, i.e. external costs caused by environmental impacts. At the research division Architectural Engineering of the KU Leuven, the MMG method was translated in an excel based tool. The life cycle financial cost calculations, based on an LCC approach, was moreover integrated in this tool, allowing for a combined assessment of environmental impacts and financial costs. In this paper the emphasis is on two methodological issues in evaluating renovation interventions, and more specific rooftop extensions: (1) the allocation of the environmental impact of the existing structures and materials to the life cycle before and after renovation and scenario analysis concerning the first life span of the building and its components and (2) energy calculations.

2.1. Allocation approach and scenario analysis concerning the first building life span

Two main approaches for accounting the environmental impact of existing structures can be distinguished in literature. The first approach excludes the environmental impact of the existing building, the second approach uses an annual depreciation and hence allocates part of the environmental impact of the first (previous) building life cycle to the second building life cycle. Several researchers use the “exclude the past” approach based on mainly two arguments: (1) the impact of the production of the remaining materials is a result of a past decision and (2) there is a lack of information concerning the type, quantity and impacts of the remaining original materials [11]. Besides the remaining materials, it should be decided how to account for the environmental impact of the demolished materials. Hansen et al. [12] argued that only materials that are still useful and with a long expected remaining service life should be allocated partially to the new second building life span.

In the “depreciation” approach the environmental impact of the remaining materials due to production and EOL of these materials is partially allocated to the new life cycle of the building according to the ratio remaining life span to the predicted first life span. An argument for this approach is that demolition of a building after a short period can be seen as deconstruction of environmental capital [13]. In this approach the estimation of the previous life span of the building is crucial as it determines the ratio of the environmental impact that should be allocated to the new life cycle.

Recent research [14] compared the two approaches on a case study of a terraced house from 1945. The results of this case study show that the choice of allocation approach does not influence the preferred choice between renovation or demolition followed by new construction. However, the estimation of the second building life span and differences in energy efficiency can affect the results significantly.

In our paper the impact of the allocated environmental cost on the total environmental cost of a rooftop extension is analyzed based on a case study. The influence of different types and ages of the original building on the final outcomes are investigated via sensitivity analyses.

2.2. Energy calculations

Two methods for estimating the operational energy use in buildings are considered in this paper and compared for a rooftop extension. The first method, the Equivalent Degree Days (EDD) method follows a static approach based on average solar radiation data for two characteristic months of the year, i.e. March and December [15]. Allacker [16] made an analysis based on two dwelling types and several insulation levels and determined an average of 1200 equivalent degree days as an appropriate value for well-insulated residential buildings in Belgium. The EDD method does not take shading into account and therefore a second method, the semi-dynamic Equivalent Degree Days method, based on semi-dynamic solar gain calculations is also considered in our analysis. This method, developed by Trigaux et al. [17] is based on the Flemish regulations regarding energy performance of buildings (EPBD) [18] and considers shading patterns, resulting from surrounding buildings, trees, sheds or side walls. The obstruction and overhang angles per window are calculated and used to determine the reduction in direct solar radiation compared to the unshaded condition.

3. Results

3.1. Detached house

To illustrate and assess the aforementioned methodological issues, a rooftop extension in the Belgian context has been analysed over a lifespan of 60 years. The existing detached building originates from 1970 and exists of one floor and an attic. The building has a floor area of 97m² and a hip roof. The hip roof is demolished, the other parts of the building remain. The existing floor of the attic is used as floor for the rooftop extension. The rooftop extension is made of semi-prefabricated wall and roof timber frame elements as described respectively in Table 1 and Table 2. The window frames are made of PVC and the total window has a U-value of 1.50 W/m²K. The total floor area of the rooftop extension is 97m², the wall area equals 78m² and the window area equals 32m². The semi-prefabricated walls and roofs were made by a rather small contractor. The construction time was the main reason to use semi-prefabricated elements instead of on-site construction. The contractor worked three days in the workplace to make the semi-

prefabricated elements, mainly manually, and one day on site for the mounting of the semi-prefabricated elements. According to the contractor the construction time would last twice as long if the elements were made on site. Despite the lower labour cost the prefabricated construction requires a higher cost for the necessary crane and prefabrication study. The contractor used semi-prefabricated elements instead of fully prefabricated elements for reasons of fixations. For the assessment, the financial data for the prefabricated parts were retrieved from the contractor, while for the other parts, data were taken from the Belgian cost database Aspen [19].

Table 1. An overview of the composition of the walls. The work sections indicated in italic are prefabricated.

Wall	U-value: 0.20 W/m ² K
External finishes - wooden claddings - larix (thickness 22 mm) - ventilated cavity	
External finishes - support structure for wooden claddings - wood Belgian mix - 38 x 38 mm - each 600 mm	
External finishes - water felt (vapour open)	
<i>External finishes - OSB board - 18 mm</i>	
Thermal insulation between wood skeleton - glass wool - 220 mm	
<i>Wood skeleton - 220 x 40 mm - each 600 mm</i>	
Internal finishes - vapour felt	
Internal finishes - support structure for boards - wood Belgian mix - 22 x 47 mm	
Internal finishes - gypsum board - 12,5 mm - screwed - width 600 mm	
<i>Internal finishes - painting on gypsum board - acrylic paint</i>	

Table 2. An overview of the composition of the roof. The work sections indicated in italic are prefabricated

Roof	U-value: 0.17 W/m ² K
External finishes - EPDM (thickness 1,2 mm) - width 1200 mm	
Thermal insulation - polyurethane board - 140 mm	
<i>External finishes - vapour felt</i>	
<i>External finishes - roof plate - OSB board - 18 mm</i>	
<i>Sloping layer - prefab wooden elements with slope - each 400 mm</i>	
<i>Wood skeleton - I beam - 300 x 60 mm - each 400 mm</i>	
Internal finishes - support structure for boards - wood Belgian mix - 22 x 47 mm	
Internal finishes - gypsum board - 12,5 mm - screwed - width 1200 mm	
<i>Internal finishes - painting on gypsum board - acrylic paint</i>	

Beside the base case, two sensitivity analyses were performed to test the allocation approach. These sensitivity analyses consider the same house, but assuming a different original construction period, i.e. 1990 and 2010. The composition of the roof and the thickness of the insulation layers of the existing dwellings are in these cases adapted to the common practice in the specific construction period (i.e. 1990 and 2010). The total environmental cost of the base case study and the two sensitivity analyses are shown in Fig. 1. On the left the basic (real) case study, the detached house from 1970, is presented, while the middle column represents the results for the same house assuming it was built in 1990 and the column on the right represents the results assuming the house was built recently, i.e. in 2010. Fig. 1 shows that the residual environmental value and EOL external cost of the existing components represent only a small share of the total environmental costs, ranging from 6% for the real case to 10% in the case of a recent building from 2010. This residual environmental cost and EOL cost of the existing components are entirely due to the removed roof. Seen the work of collecting data of the existing structure and the small differences of the allocated impact between old and new buildings, we can conclude that it is not an added value to use the depreciation approach in the case of a rooftop extension.

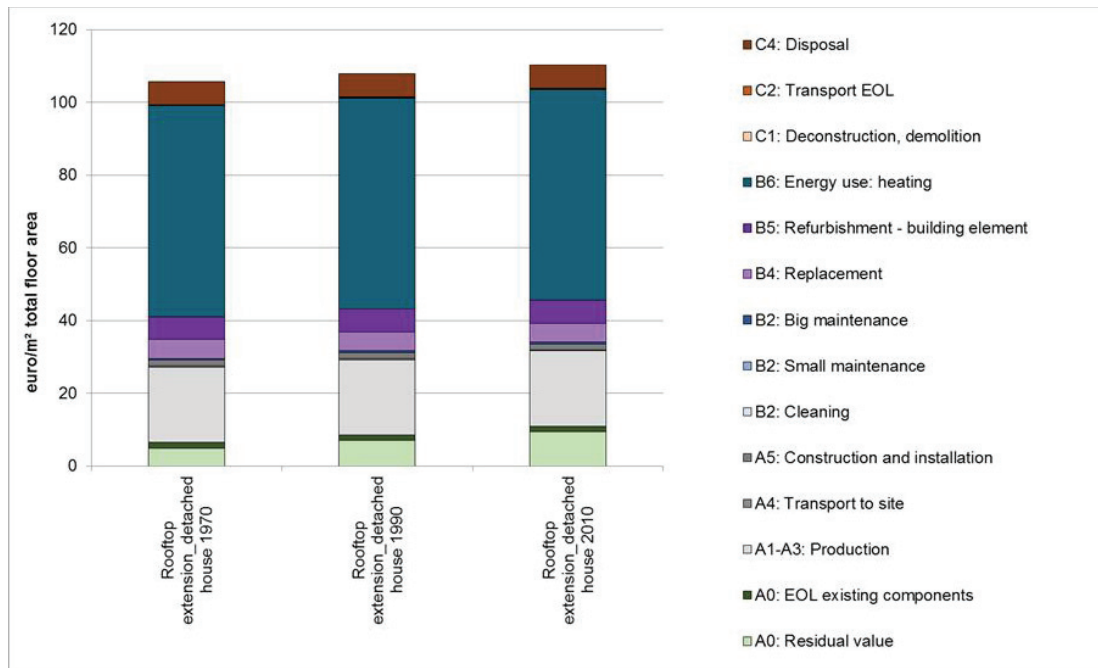


Fig. 1. Total Environmental Cost for the rooftop extension on a detached house from 1970 (left), 1990 (middle) and 2010 (right)

In a next step, the two calculation methods for the estimation of the operational energy use were applied and compared by analysing various insulation levels of the rooftop extension. In the results presented in Fig. 1, the static EDD method was used for the insulation level as presented in Table 1 and Table 2. In a next step, these results are compared with the outcomes of a rooftop extension with elements with a lower heat resistance, but still fulfilling the current Energy Performance (EPB) requirements in Belgium, i.e. walls and roofs with a U-value of 0.24 W/m²K instead of respectively 0.20 and 0.17 W/m²K. These options are indicated by the term “EPB” in the figures. The operational energy of each scenario is calculated in three ways, based on: (1) static EDD (1200eq°d), (2) semi-dynamic EDD (D.eq°d) assuming there are similar detached houses surrounding the building and (3) semi-dynamic EDD assuming there are apartment blocks of five floors surrounding the building (D.eq°d). The results are shown in Fig. 2 (life cycle environmental external cost) and Fig. 3 (life cycle financial cost).

Fig. 2 first of all shows that the operational energy is causing nearly 60% of the life cycle environmental impact of the rooftop extension, and hence an accurate estimation is important. For the base case, the environmental cost for operational energy use calculated with the semi-dynamic EDD method is 7% higher than when calculated with the static EDD method, assuming that detached houses are surrounding the building. When apartment blocks of five floors are surrounding the building, the semi-dynamic EDD method results in 18% more environmental costs for operational energy use than when using the static EDD method. For the variant with the lower insulation level, the semi-dynamic EDD method results in an increase of the environmental cost for energy of 13% compared to the results calculated with the static EDD method, assuming that detached houses are surrounding the building. When the analysed building is surrounded by five floor high apartment blocks, the energy (environmental) cost calculated with the semi-dynamic EDD method is 24% higher than when calculated with the static EDD method. When looking at the financial cost, Fig. 3 shows that in this case study energy use is responsible for approximately 9% of the life cycle financial cost. As the energy cost is responsible for less than 10% of the life cycle, the different methods and sensitivity analyses do not lead to large differences. From this analysis, we can conclude that the static EDD method, assuming 1200 equivalent degree days, seems to be a good approximation for the energy calculations of a typical rooftop extension in the Belgian context. Nevertheless, for specific situations with high shading conditions and/or lower U-values, the semi-dynamic EDD method is recommended.

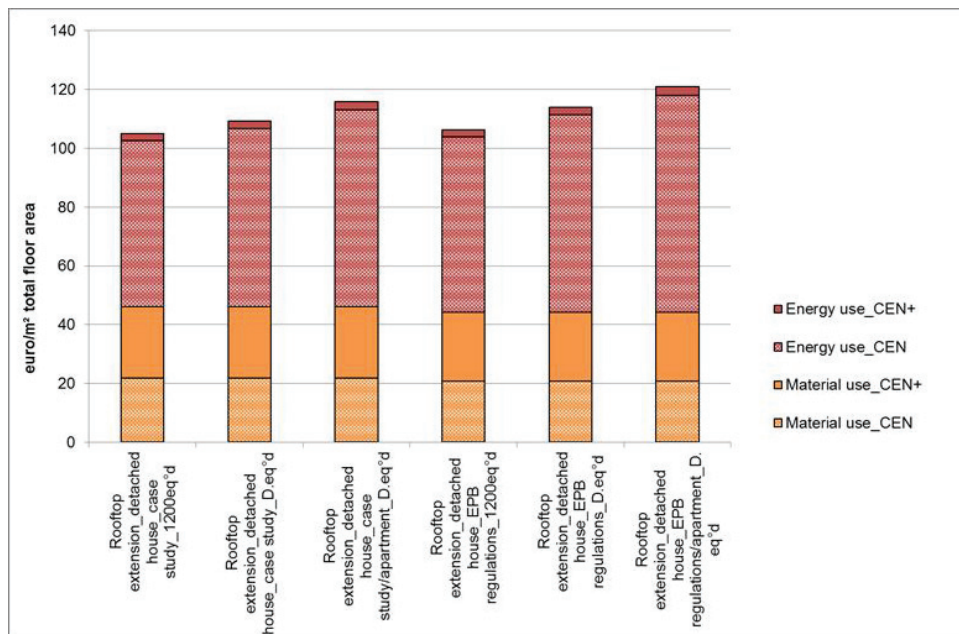


Fig. 2. Environmental Life Cycle Cost, subdivided in material use and energy use

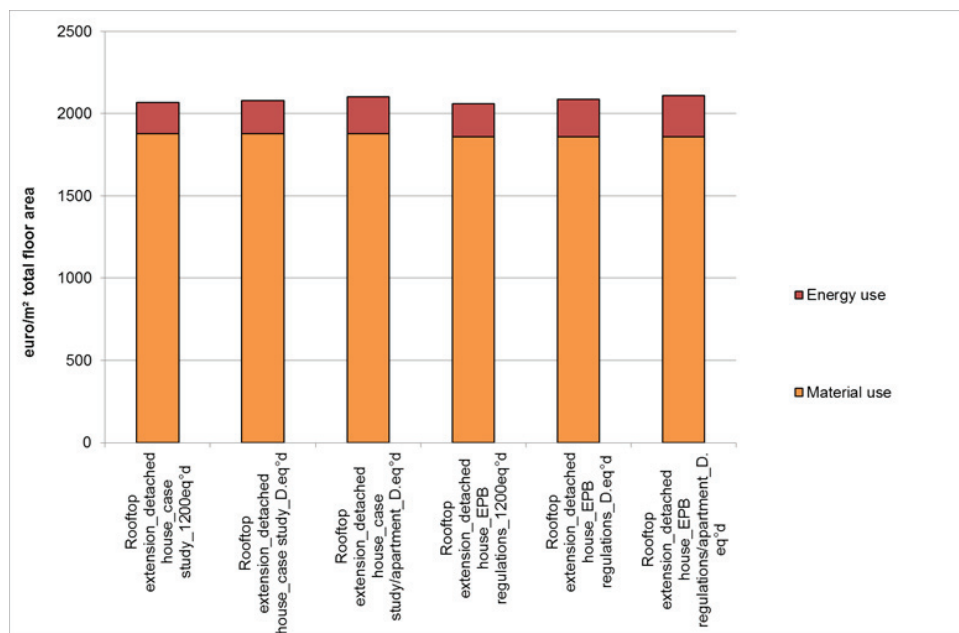


Fig. 3. Financial Life Cycle Cost, subdivided in material use and energy use

The next paragraphs focus on the different building elements in more detail. At the element level, the operational energy is not considered. Fig. 4 and Fig. 5 show the life cycle environmental and financial cost of the semi-prefabricated timber frame walls, subdivided per work section. The work sections with the highest environmental impact are the ones based on wood. 29% of the total material impact is due to the timber frame. The OSB board and

the wooden claddings are responsible for respectively 15% and 22% of the total material impact, the thermal insulation for 14%. From a financial point of view, the wooden claddings (30%), the gypsum board (12%) and the painting (22%) have the highest cost, mainly due to the fact that they must be replaced during the life span of 60 year of the building element. The wood skeleton and the thermal insulation have, in contradiction to the environmental cost, only a share of respectively 10% and 5%. It has to be noted that the skeleton walls are conceived as such that these cover the cavity of the existing wall as the skeleton provides the connection of the outer leaf to the inner leaf of the existing wall. The section of the wood skeleton are however bigger than necessary for reasons of structural stability.

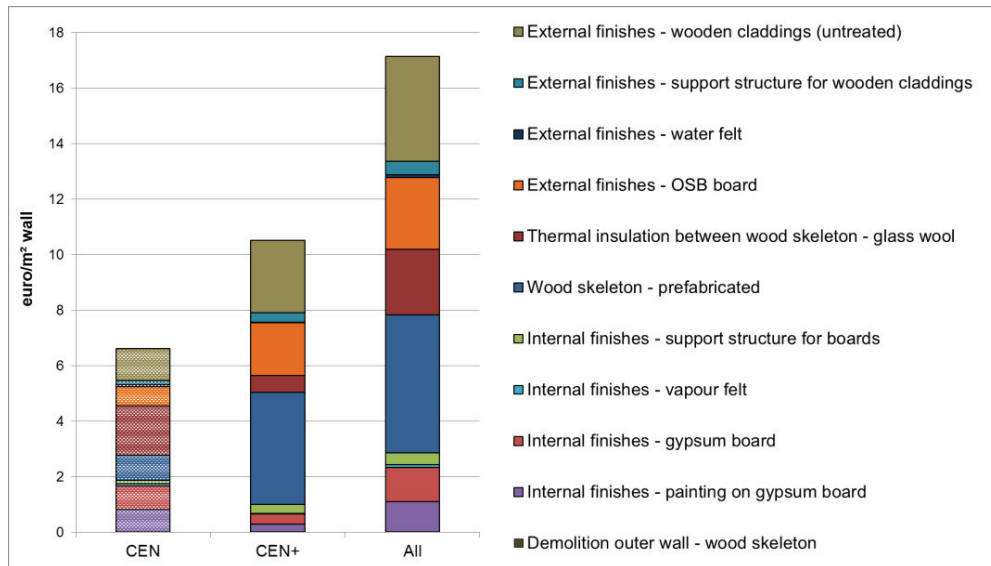


Fig. 4. Life Cycle Environmental Cost of the semi-prefabricated timber frame walls, subdivided per work section

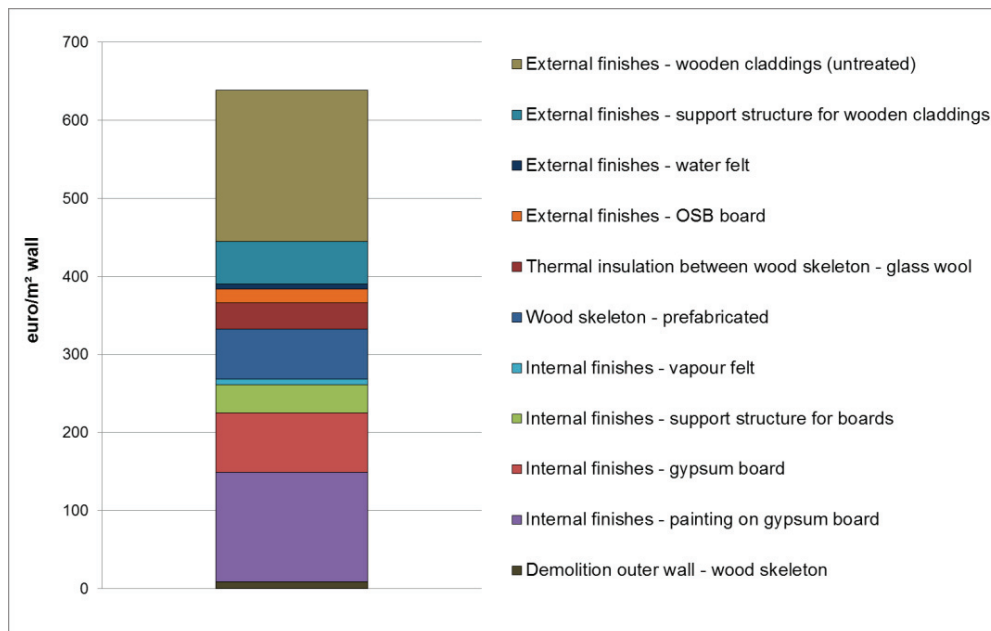


Fig. 5. Life Cycle Financial Cost of the semi-prefabricated timber frame walls, subdivided per work section

In Fig. 6 and Fig. 7 the same assessment is made for the semi-prefabricated roof elements. The thermal insulation of polyurethane has the highest environmental impact (30%), followed by the wood skeleton (19%) and the OSB board (20%). The internal finishing in gypsumboard and painting have an impact of respectively 13% and 21%. From a financial point of view, the EPDM (27%), the gypsum board (12%) and the painting (17%) have the highest cost, mainly due to the fact that they must be replaced during the life span of 60 year of the building element. The wood skeleton and the thermal insulation have a share of respectively 11% and 9%.

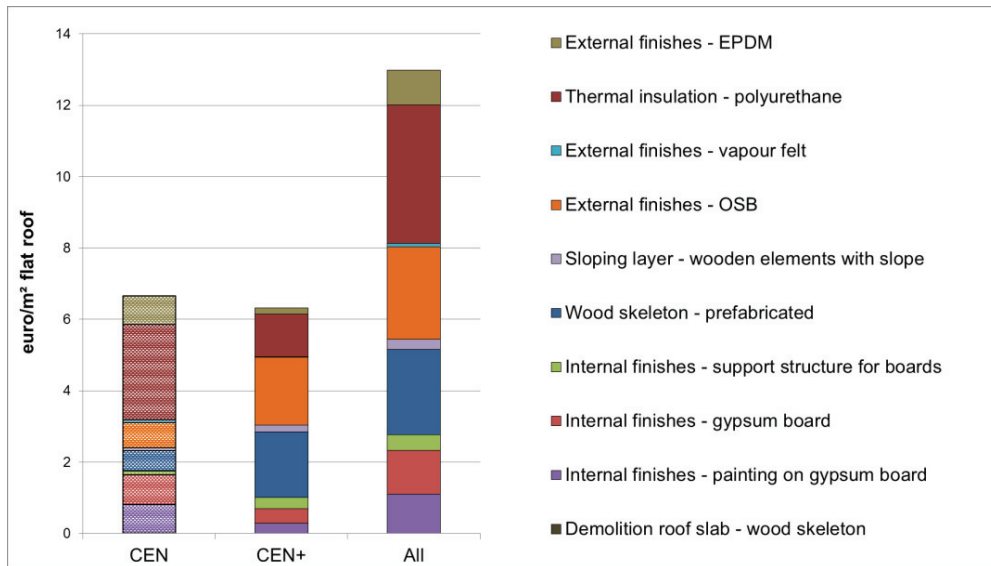


Fig. 6. Life Cycle Environmental Cost of semi-prefabricated timber frame roofs, subdivided per work section

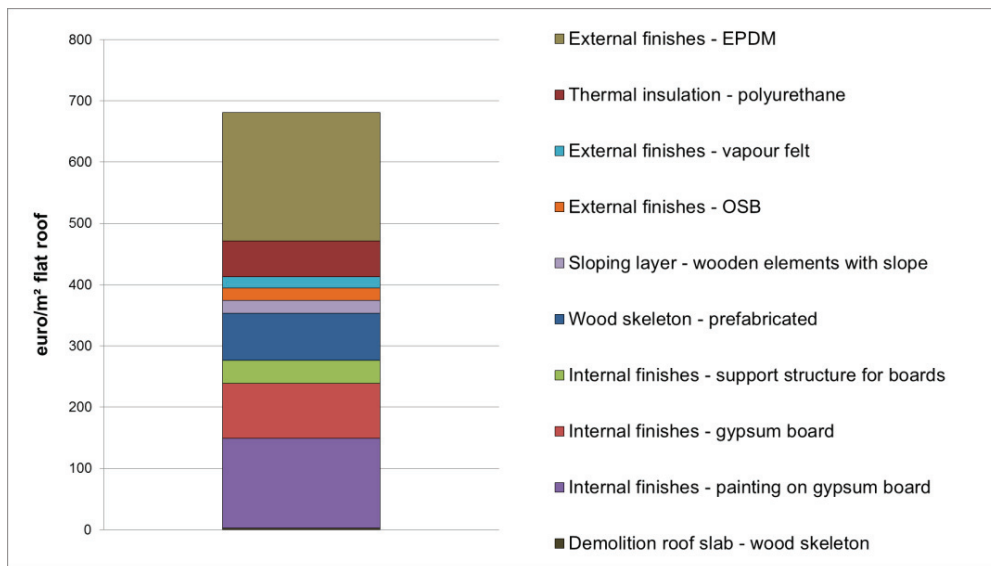


Fig. 7. Life Cycle Financial Cost of the semi-prefabricated timber frame roofs, subdivided per work section

Seen the high environmental impact of the wood-based work sections, a more detailed analysis of these is made. The high impact is mainly due to the end-of-life processes (EOL) of these works sections. Analysis of the Ecoinvent

record used for the end-of-life process of wood learns that it includes chromium. However, chromium is no longer used in Belgium for the preservation of construction wood. In order to get an idea of the influence of chromium on the EOL cost, the chromium is removed from the Ecoinvent record. The results are shown in Fig. 8 (semi-prefabricated timber frame walls) and Fig. 9 (semi-prefabricated timber frame roofs).

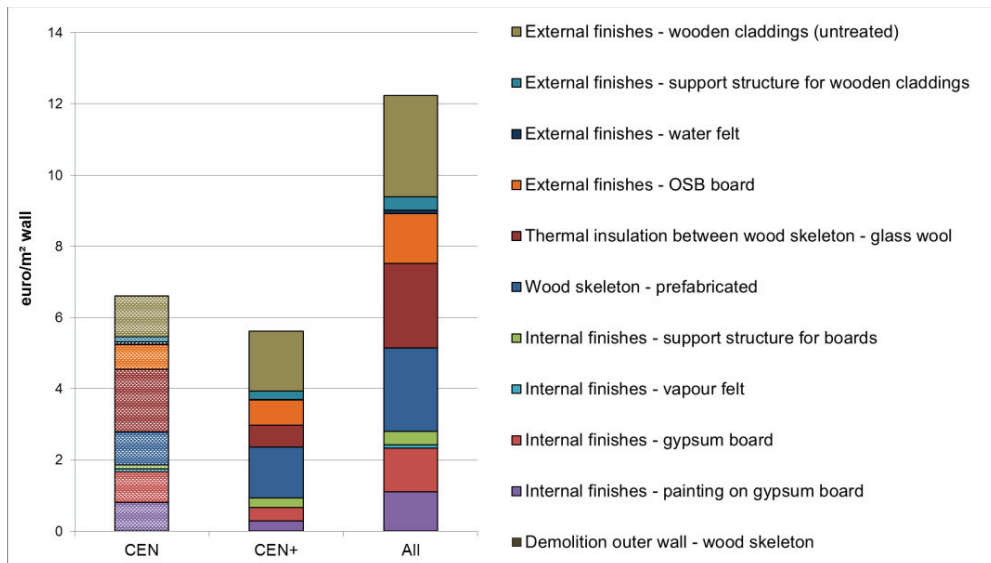


Fig. 8. Life Cycle Environmental Cost of the semi-prefabricated timber frame walls, subdivided per work section, without chromium preserved wood

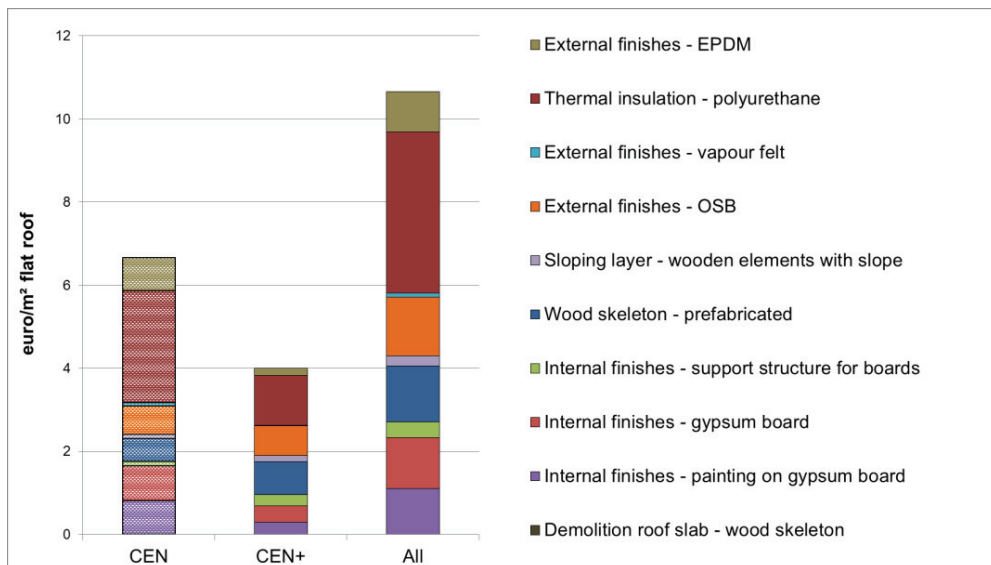


Fig. 9. Life Cycle Environmental Cost of the semi-prefabricated timber frame roof, subdivided per work section, without chromium preserved wood

In the case of the semi-prefabricated timber frame walls, the impact of the wood skeleton and the OSB board to the total environmental impact decreases respectively from 29% to 19% and from 15% to 11%, when chromium is

removed from the inventory records. The wood skeleton and the thermal insulation have now an equal environmental impact. For the semi-prefabricated roof elements, the impact of the wood skeleton and OSB board decreases from approximately 20% to 13% when chromium is removed, while the impact of the insulation increases to 36%. In this first analysis, no substitutes for the chromium were added to the record. Consequently, it can be assumed that the shown environmental cost may be an underestimate of the real environmental cost. Further research on the composition of wood preservatives is still ongoing but not yet completed at the moment of writing.

3.2. Terraced house

To ensure that the conclusions regarding the allocation approach and energy calculation method are also valid for other building types, the same analysis is made for a rooftop extension on a terraced house. The existing terraced house originates from 1970 and consists of two floors and an attic. The building has a floor area of 140m² and a pitched roof. For both methodological issues, the same conclusions can be drawn for the terraced house. The residual environmental value and EOL external cost of the existing components also represent only a small share of the total environmental costs, from 7% in the case of building from 1970 till 11% in the case of a recent building from 2010. The energy cost calculated with the semi-dynamic EDD method is a slightly lower (from 6% till 9%) for a terraced building surrounded by other terraced buildings than when calculated with the static EDD method.

4. Conclusions and recommendations

In this paper two methodological issues in evaluating renovation interventions, and more specific rooftop extensions are analyzed: (1) the allocation of the environmental impact of the existing structures and materials to the life cycle before and after renovation; and (2) the energy calculation method. Concerning the first methodological issue, the “exclude the past” approach and the “depreciation” approach are compared. The differences between the two approaches are rather small in the analyzed case studies in the Belgian context. Previous research [14] furthermore shows that the choice of allocation approach does not influence the overall conclusions regarding the preferred choice between renovation or demolition and new construction. Together with these results we can conclude that using the depreciation approach is not an added value in the decision-taking process in the case of a rooftop extension.

For the estimation of the operational energy use, the static and semi-dynamic Equivalent Degree Days (EDD) methods have been compared. The static EDD method, based on 1200 equivalent degree days, seems to be a good approximation for the energy calculations of a typical rooftop extension in the Belgian context, for well insulated buildings and when shading of the surrounding is rather limited. In some specific situations, i.e. lower insulation level of the rooftop extension and/or high shading conditions, it is recommended to use the semi-dynamic EDD method.

Furthermore, the wall and roof semi-prefabricated timber frame elements are assessed both from an environmental and financial perspective over their whole life cycle of 60 year. Optimizing the work sections based on wood may have the largest environmental reduction. However, the composition of the wood preservatives should be further analysed to validate this conclusion. For the roof elements, the thermal insulation in polyurethane has a high environmental cost. The finishing layers have in both elements the highest financial cost due to the fact that these are replaced during the life cycle of the element/building.

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